CoSMo

Modeling Error Source Attribution During Motor Adaptation

By: EAGEr BEAVeRS

(<u>**E**</u>lucidating <u>**A**</u>ttribution <u>**G**</u>iven <u>**Er**</u>rors <u>**B**</u>y <u>**E**</u>stimating <u>**A**</u> <u>**Ve**</u>ctor <u>**R**</u>egression <u>**S**</u>olution**)**

Arunachalam AG, Boehm WB, Ruttle JE, Yang CS

University of Minnesota

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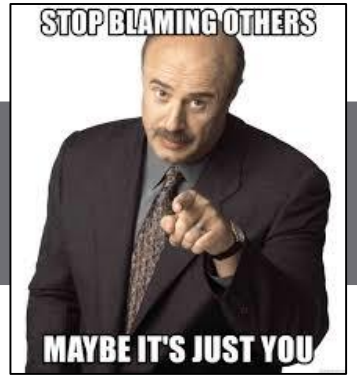
Phenomenon: Adaptation

Error probably due to **external** factors **(the world)**

Solution

Compensate for wind



Error probably due to **internal** factors **(the body)**

Change muscle coordination, etc.

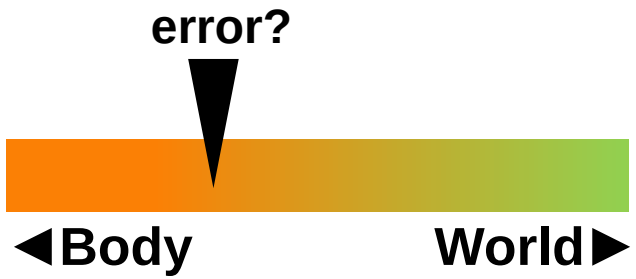
How do you identify the source of the error?

Phenomenon, Cont'd

Large errors = attributed to world

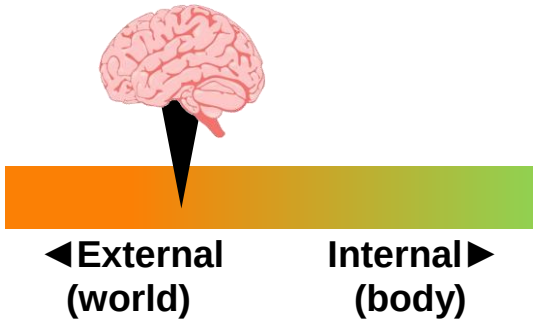
Small errors = attributed to body

Wilke et. al, 2013



Question

*How is **motor error** attributed to the **body** and the **world**?*



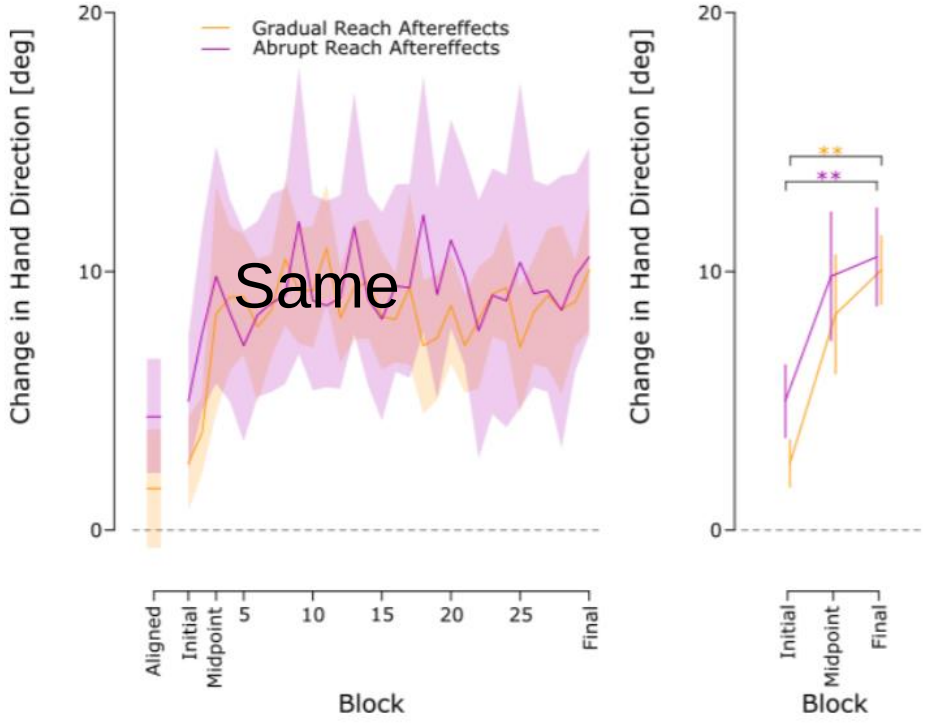
Objectives

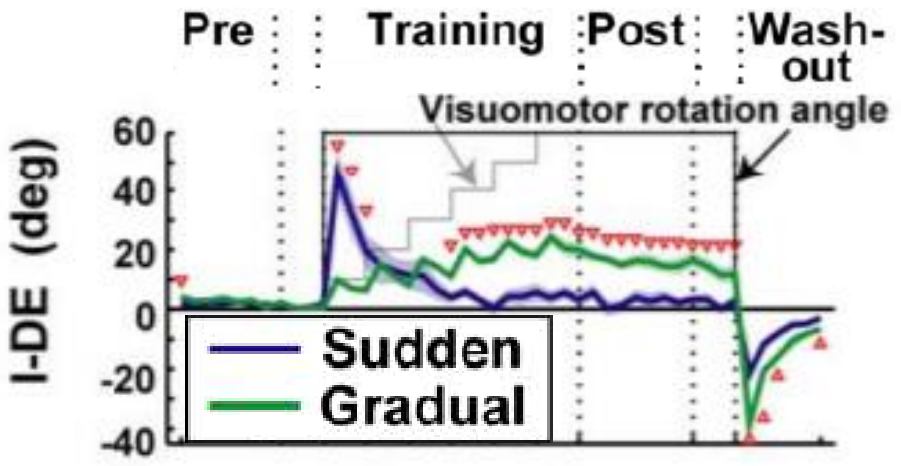
- Model how sensory prediction errors are **attributed to body and world** factors

Background Motivation

- Current models **cannot** predict source attribution from sensory prediction error alone

- Conflicting experimental results for small and large errors





Saijo & Gomi.,2010

Different

Background, Cont'd

Estimating the sources of motor errors for adaptation and generalization

Max Berniker[1,2] & Konrad Kording[1,2]

nature neuroscience

Constant World / Body Factors → *Internal Model Parameters* → *Arm Kinematics*

Background, Cont'd

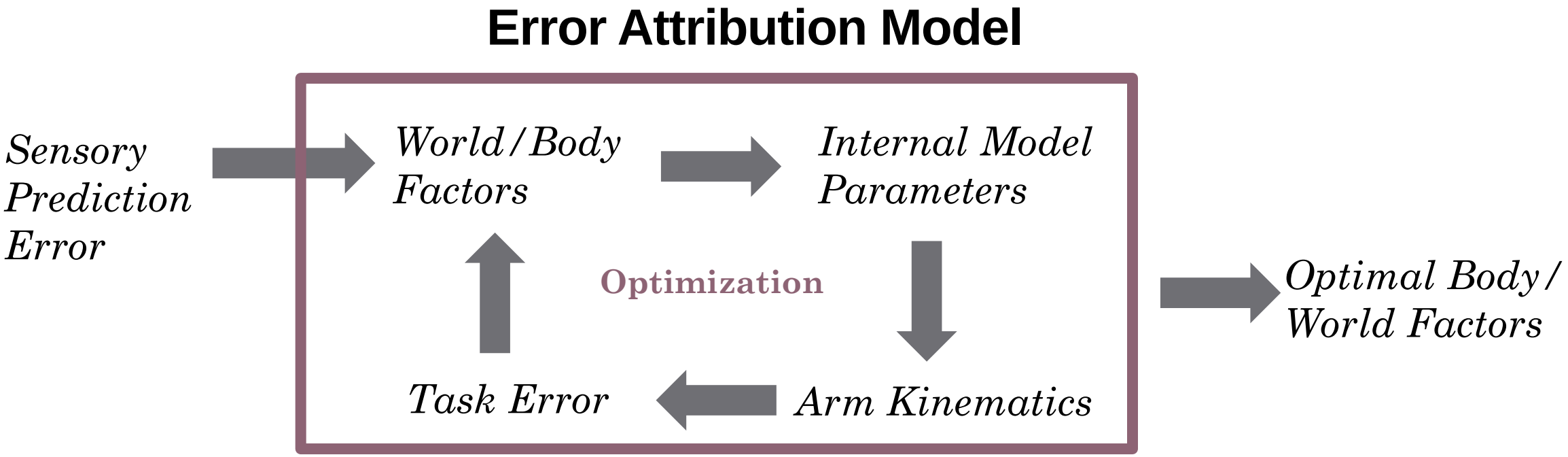
Estimating the sources of motor errors for adaptation and generalization

Max Berniker[1,2] & Konrad Kording[1,2]

nature neuroscience

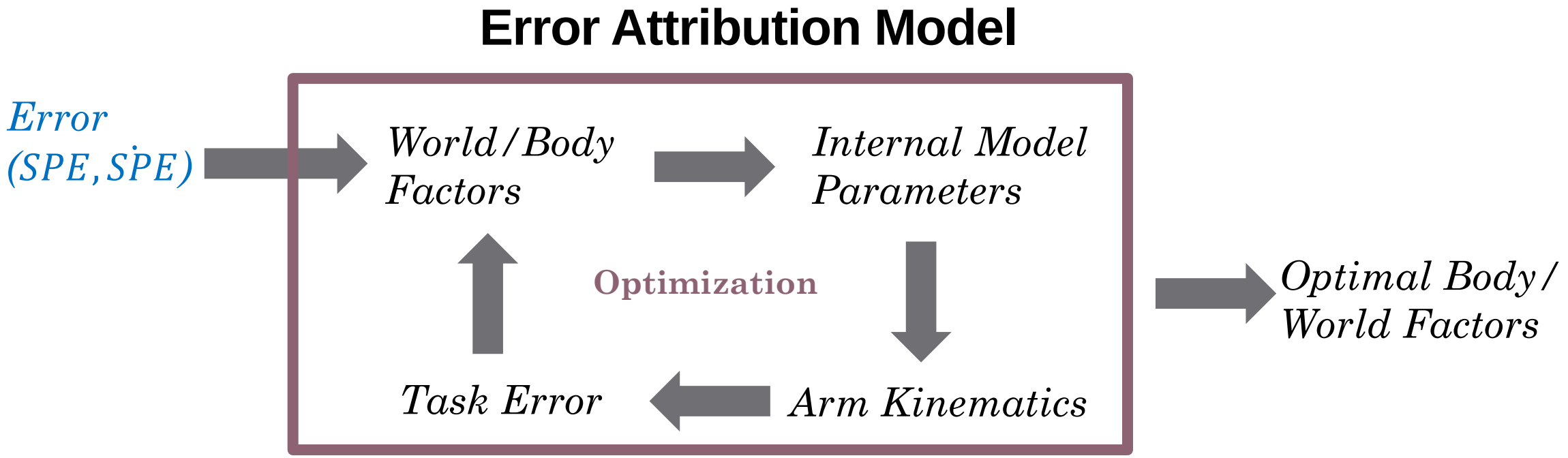
Motor Errors → *Dynamic World / Body Factors* → *Internal Model Parameters* → *Arm Kinematics*

Project Overview



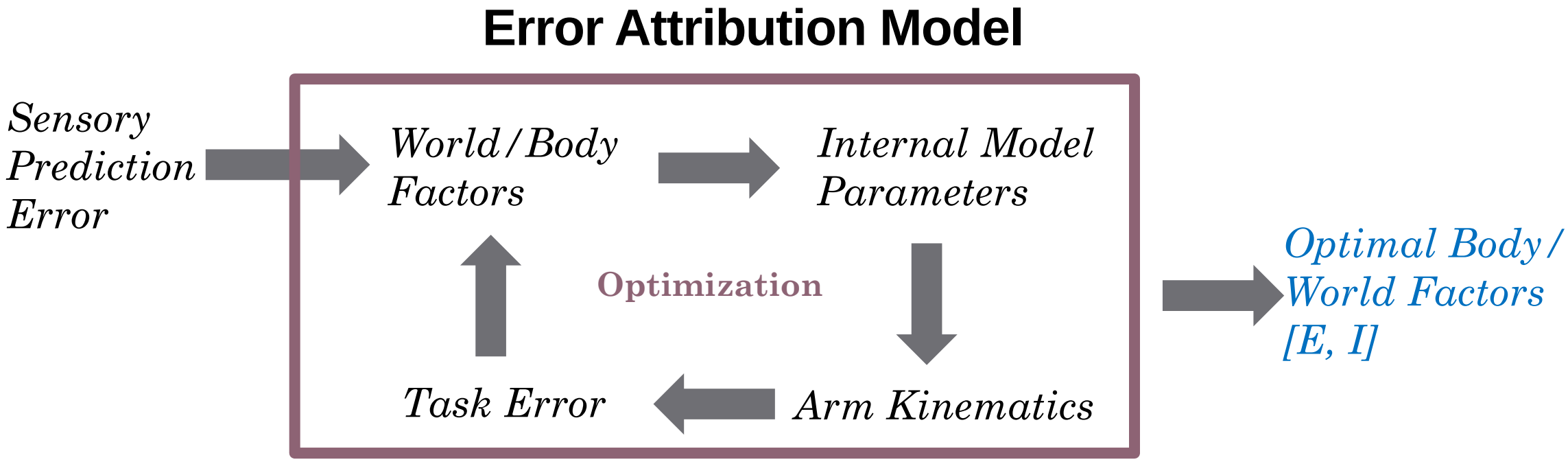
Parameters & Variables

Inputs



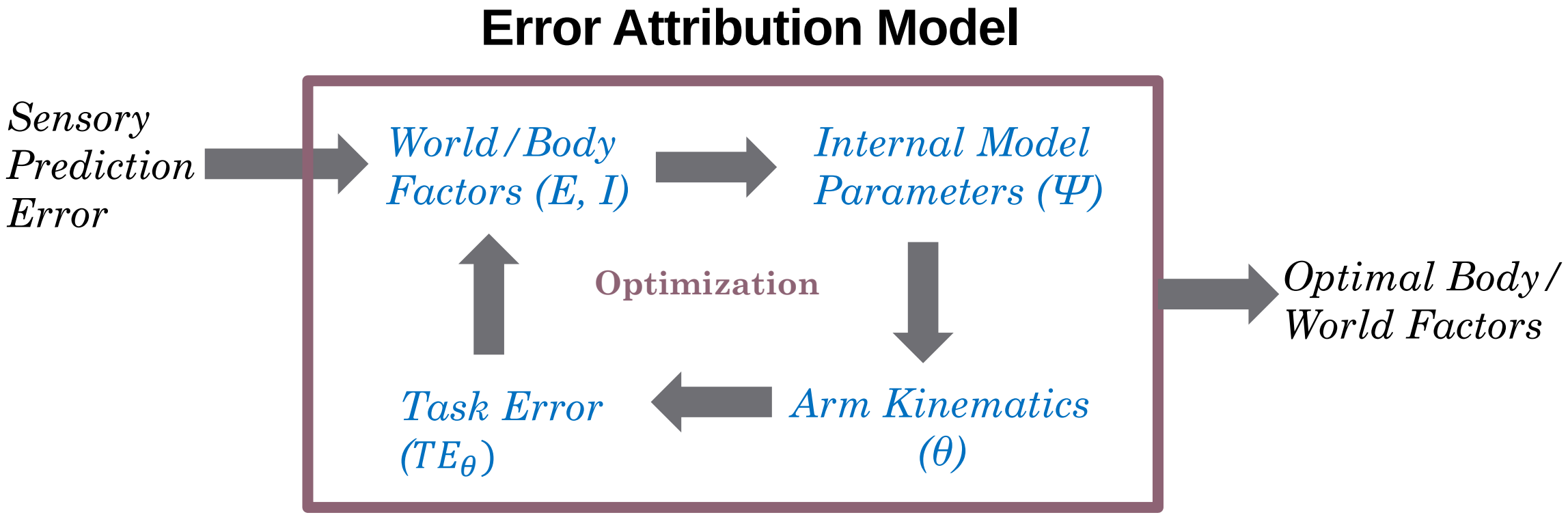
Parameters & Variables

Outputs



Parameters & Variables

Latent variables



Parameters & Variables

Error Attribution Model

Created by Us:

$f(SPE) =$ **Error Attribution [*E,I*]**

Inputs

$\boldsymbol{SPE}$: **Sensory Prediction Error**

$\boldsymbol{\dot{SPE}}$: **Rate of Sensory Prediction Error**

Outputs

$\boldsymbol{I}$: **Level of attribution to body (internal)**

$\boldsymbol{E}$: **Level of attribution to world (external)**

Adaptation Component

Modified:

Internal Model Parameter Updates

Borrowed:

State Estimation

Berniker & Kording, 2008

Internal Model Parameters $[\boldsymbol{\psi}]$

Body

- **Arm Inertia**
- **Joint Damping**

World

- **External Forces on the Hand**

States $[\boldsymbol{\theta}]$

- **Shoulder & Elbow Joint Angles**
- **Shoulder & Elbow Joint Angular Velocities**

Hypothesis

Hypothesis 1:

Small external perturbation → **small** initial $SPE, \dot{SPE}$

Small errors will change the variance around the estimates of **body-centric** internal model parameters

Hypothesis 2:

Large external perturbation → **large** initial $SPE, \dot{SPE}$

Large errors will change the variance around the estimates of **world-centric** internal model parameters

Simulated Experimental Paradigm

Center-out Reaching Task in Force Field

$F_{\perp hand} \propto ||v_{hand}||$

Assume humans use minimum jerk trajectory

- Simulate path with no adaptation using **small** and **large** viscous force fields ($F_{\perp hand}$)
- Extract SPE $(y - \hat{y})$ and $S\dot{P}E$ $(y \dot{-} \hat{y})$to use in regression for finding $[E, I]$

Toolkit

1. Regression
2. Global optimization
3. Kalman filtering

Toolkit: Model Fitting & Optimization

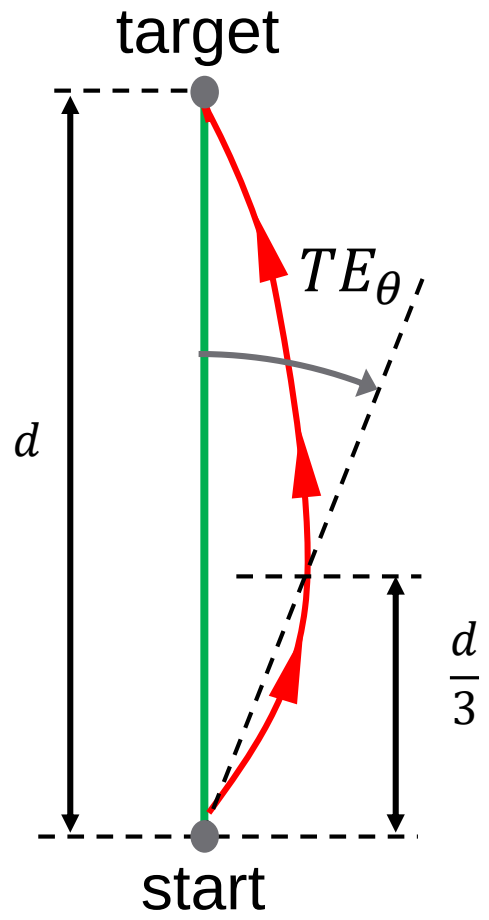
Estimation of Source Attribution Levels

1. Regression

$$I = |a_1 SPE + a_2|$$

$$E = |b_1 SPE|$$

2. Optimize: Find *E* & *I* that Minimize Steady State Target Error, TE_θ



Step into adaptation model →

Toolkit: Kalman Filter

Adaptation: Internal Model Parameter Update

At time step *1*:

$[I, E]_1$

Set initial covariance matrix

$Q_{\psi} = \begin{bmatrix} \propto I_k^2 & 0 \\ 0 & \propto E_k^2 \end{bmatrix}$

Step through trials until steady state TE_{θ_k}

K
Kalman gain changes

ψ
Parameters Update

θ
States Update

At Steady State?

NO

YES

TE_{θ_k}

Step Out To Optimizer →

Predictions

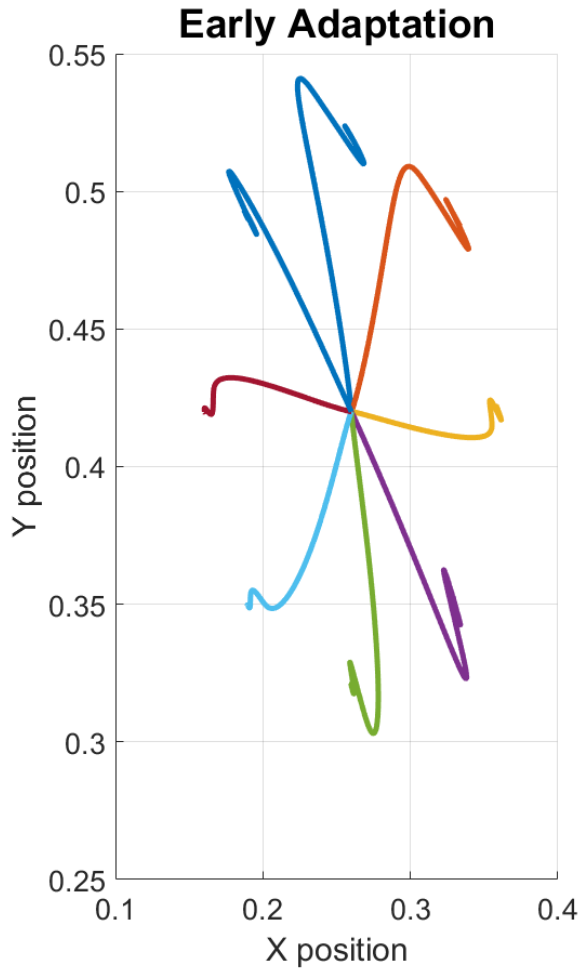
Prediction: Increased SPEs will be attributed to the world and small SPEs will be attributed to the body

$$\frac{E}{I} = Source\ attribution$$

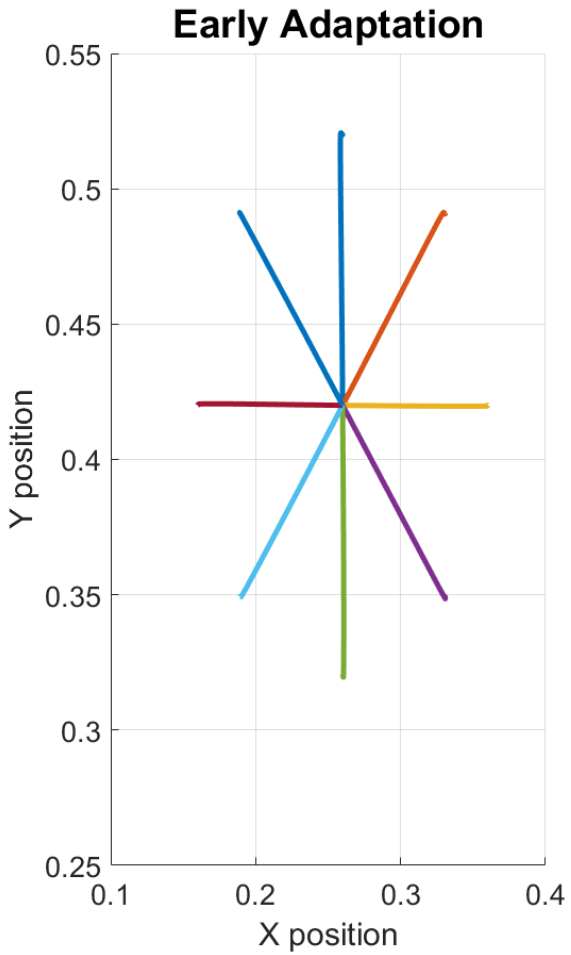
Increased E/I = world attribution

Decreased E/I = body attribution

Results: Optimization yields improved learning parameters for large errors



Results: Optimization yields poor learning parameters for small errors



Results: E and I values change in expected directions

	E	I	E/I	Min Cost
Initial	.040	.010	.400	N/A
Large	.017	.035	.480	.161
Small	.0005	.044	.010	.210

1. Small errors will increase the variance around body-centric internal model parameter estimates (relative to world-centric variance
2. Large errors will increase the variance around world-centric internal model parameter estimates(relative to body-centric variance

Model Testing

Hypothesis Revisited

*How is **motor error** attributed to the **body** and the **world**?*

1. Large SPEs are attributed to the world
2. Small SPEs are attributed to the body

Critical Model Evaluation

Strengths of our model:

- Conceptually simple
  - Few additional parameters
- Interpretable
  - Change in model parameters directly relate to changes in real world parameters
- Makes predictions about how representation in an internal model
  - Useful for model validation

Future Directions

- Improve our model's learning of small errors
  - Optimize for more parameters (rate of SPE, rate of task error)
- Validate model by comparing to experimental data
- Consider biological plausibility of out model

Summary & Conclusions

- The body may differentially attribute movement errors to the body or world based on the magnitude of the SPE
  - Large errors attributed to the world
  - Small errors attributed to the body

Many thanks for guidance from Konrad, Paul, & Gunnar

Thank you for listening!

Questions?

Equations

Parameter Updates: Dynamics

Parameter Dynamics:

$$\psi_{k+1} = \alpha I \, \psi_k + \varepsilon$$

α is forgetting factor

$\varepsilon \sim N(0, Q_\theta)$ ←*fictitious*

Fictitious Observer:

$$\varphi_k = \left[\frac{\partial e}{\partial \psi}\right] \vec{e}$$

$\sim N(0, R_\varphi)$

Jacobian = H

Equations

Prior Covariance:

$$\mathbf{P}_{k+1|k} = cov(\boldsymbol{\psi}_{k+1|k})$$

$$= \mathbf{A}^{\mathbf{T}}\mathbf{P}_{k|k}\mathbf{A} + \mathbf{Q}_{\boldsymbol{\theta}}$$

Observation Covariance:

$$\mathbf{R}_{\boldsymbol{\varphi}} = cov(\boldsymbol{\varphi}_k)$$

Kalman Gain:

$$\mathbf{K}_{k+1} = \frac{\mathbf{P}_{k+1|k}\mathbf{H}^{\mathbf{T}}}{\mathbf{R}_{\boldsymbol{\varphi}} + \mathbf{H}\mathbf{P}_{k+1|k}\mathbf{H}^{\mathbf{T}}}$$

Posterior Covariance:

$$\mathbf{R}_{k+1|k+1} = (\boldsymbol{P}^{-1} + \boldsymbol{H}'\boldsymbol{R}\boldsymbol{H})^{-1}$$

Update:

$$param_{k+1} = param_k + k_{k+1}(\overbrace{y - \hat{y}}^{SPE})$$

Project Overview

Error Attribution Model

$SPE, S\dot{P}E$

From perturbed reaching task

Goal: minimize target error

Guess attribution to each of body & world factors, estimate associated task error

Adaptation Model Component
Simulate adaptation to perturbed reaching task until steady state & output target error

Keep guessing until I & E that minimize error found

I **Level of error attribution to body (internal)**

E **Level of error attribution to world (external)**